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The choice of reference study period in building LCA – case-based analysis and arguments

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Abstract. Introduction: In building LCAs, the calculations are carried out over a chosen reference study period (RSP), which is commonly set around 50-60 years. When developing the Danish LCA method for DGNB certification, and later for the preparation of the voluntary sustainability class for the building code, longer RSP's were suggested by technical committees. Therefore, the RSP has been based on a technical approach to the lifetime of buildings, assuming 80 years for offices, 100 years for hospitals and 120 years for residential buildings. In this study, the effects and arguments of a shorter RSP are investigated. Method: LCA-based carbon profiles of 11 building cases were carried out to compare how the RSP influences the results. RSPs of 50, 80, 100 and 120 years were investigated. The building cases represent different use types, structural systems, material choices, on-site electricity generation and installation scope. Results: Results show no notable difference in ranking, the building cases in-between, at RSPs of 50 and 120 years. Further, the relationship between the best and the worst performing building stays around a three-fold difference, regardless of the RSP. Conclusion: The longer RSPs have serious drawbacks regarding the increasing uncertainties associated with the scenarios. Further, annualizing results of longer RSPs entail a fundamental ethical issue of effectively allocating environmental loads to future generations. These specific drawbacks of uncertainty and impacts distribution are reduced by using an RSP of 50 years. The RSP of 50 years thus represents a compromise between ensuring that impacts from replacements of shorter-lived building materials will be reflected in the results, and between encouraging that more emphasis can be put on the crucial material related emissions that affects the global carbon budgets here and now.

1. Introduction

Life cycle assessment is used in many sectors as a decision-making tool for optimizing the environmental performance of products and services. The main advantage about LCA is the ability to include exchanges with the environment throughout the supply chain, popularly termed 'from cradle to grave'. However, for the building sector in particular, the way from cradle to grave may be lengthy. LCA on buildings typically deal with operational and embodied impacts: Operational impacts being the impacts related to the energy supply for the buildings operation, and the embodied being the impacts related to the production, replacement and end-of-life of the materials [1]. It is widely recognized how the reference study period used to calculate the LCA of a building, affect the impacts from embodied as well as operational processes. Hence, a longer RSP entails higher impacts in total, although the impacts per year are reduced due to the higher number of years on which to distribute the 'original' materials' emissions [2,3].

Currently, the considerations about choice of RSP are in focus in the Danish building sector. Based on recent focus from national policies, initiatives are made to develop a voluntary sustainability code in the building regulation. Whole building LCA will form a substantial part of these requirements, and further



methodological investigations and adaptations of the current method is thus needed. In the Danish building sector and DGNB certifications, a harmonized LCA method is in use, adapted from the DGNB International scheme. In this adapted approach, the RSPs are set per building type, i.e. 80 years for offices, 100 years for schools and hospitals and 120 for residential buildings. These RSPs were chosen by a DGNB Denmark technical committee by reference to a national research report on service life of buildings and building materials published in 2013 [4]. In the service life research report, these RSPs are derived as the expected, ‘actual’ service life of new Danish buildings. Using these RSPs further align with the EN 15978 guidelines about using the required service life of a building as default RSP. However, research practice and international certification schemes, e.g. DGNB International and Level(s), predominately uses 50 years or 60 years as RSP [5–7] across different building types. The choice of 50 and 60 years is not related to the expected technical service life of the building, but is consistent with the depreciation principles for construction investments [8].

The choice of 50 years versus the 80-120 years is thus considered as part of the further development of a harmonized Danish method for use in DGNB and building regulations. This regulation of the building sector is a key parameter in achieving the Sustainable Development Goal 11 of sustainable cities and communities. The aim of this paper is to investigate the following questions: 1) Will a change in the RSP affect the ranking of results from buildings under study? 2) Which specific pros and cons are associated with the different approaches to RSP definitions?

2. Method

11 building cases are modelled in accordance with the harmonized method used in the Danish DGNB certification scheme. The 11 cases were chosen to represent a broad selection of features concerning function, main materials as well as the amount of central technical installations, e.g. photovoltaics. For reasons of simplicity only the impact category of global warming potential (GWP) is included in this analysis. The functional equivalent is set per m² GFA over the RSP in question, i.e. calculations are made for RSPs 50, 80, 100 and 120 years. The modelling includes the following life cycle stages: A1-A3 production, B4 replacements, and C3-C4 waste treatment and disposal. Building elements included are foundation/basement and structure, envelope and internal structures and partitions, finishes and central technical aggregates. For some cases, ventilation ducts and piping is furthermore included (see details in Table 1). The modelling is done with LCAByg, a nationally developed tool that uses the Ökobau database version 2016 as background environmental data. The expected service life of building materials under Danish conditions are specified in the service life table by Aagaard et al. [4]. Materials are replaced in the model at the end of the service life specified in the service life table. Table 1 presents the building cases included in the analysis. Further details about the harmonized LCA method and LCAByg can be found in [9].

Table 1. Details of the 11 case buildings.

Case #	Building type	Characteristics	PVs	Installations in calculation
1	Residential, multi-storey	Concrete foundation and ground slab with EPS insulation. Massive wood construction (CLT), cellulose-based insulation for walls, mineral wool for roof,	No	Only central aggregates
2	Office	Concrete foundation with EPS insulation. Concrete slabs and wall elements with mineral wool. Built-up roof	Yes	Only central aggregates
3	Office	Concrete foundation with EPS insulation. Concrete slabs and wall elements with mineral wool. Built-up roof	No	Central aggregates and distribution systems
4	Office	Concrete foundation with EPS insulation. Concrete slabs. Modular façade elements with mineral wool, glazing and aluminium frame. Built-up roof	Yes	Only central aggregates

5	Residential, multi-storey	Concrete foundation with EPS insulation. Concrete slabs and concrete wall elements with mineral wool and front clay tiles. Built-up roof	No	Central aggregates and distribution systems
6	Residential, terraced houses	Concrete foundation and ground slab with EPS insulation. External wall of wood frame, mineral wool and fibre cement boards. Apartment partitions in lightweight concrete. Slabs in wood. Built-up roof	Yes	Only central aggregates
7	Hospital	Concrete foundation and ground slab with EPS insulation. Concrete slabs and concrete wall elements with mineral wool and front clay tiles or enamelled glass. Built-up roof	Yes	Central aggregates and distribution systems
8	Residential, terraced houses	Concrete foundation and ground slab with EPS insulation. Concrete slabs and concrete wall elements with mineral wool and front clay tiles. Roof construction in CLT with mineral wool insulation and bituminous sheets	Yes	Not included
9	Residential, single-family	Concrete foundation and ground slab with EPS insulation. Concrete slabs and concrete wall elements with mineral wool and front clay tiles. Hip-to-hip roof construction in timber, mineral wool insulation and tiles	No	Central aggregates and distribution systems
10	Residential, multi-storey	Concrete foundation. Concrete slabs with mineral wool, fibre cement boards. Concrete balconies with steel sheet covering. Built-up roof	Yes	Only central aggregates
11	School	Concrete foundation and ground slab with EPS insulation. Concrete slabs and concrete wall elements with mineral wool and aluminium covering. Built-up roof	Yes	Central aggregates and distribution systems

3. Results

Figure 1a presents the GWP profiles of the life cycle stages whose aggregated results are constant regardless of the RSP, i.e. production and EoL impacts of the 11 cases of the current study. The figure shows these constant values distributed over the RSPs in question. The impacts range between 2.7-9.8 kg CO₂e/m²/year for the 50-year RSP. The range diminishes to 1.2-4.1 kg CO₂e/m²/year for the 120-year RSP and the relative difference between single projects remain constant.

Figure 1b presents the GWP profiles of the replacement stage impacts at different RSPs. These figures vary in a non-linear approach, reflecting how the specific construction and material choices of the cases result in different patterns of replacements. For shorter RSPs, e.g. 50 years, only materials and building parts with limited service life, such as indoor/outdoor paint and thermo-glazing in windows, will be replaced. However, for longer RSP's, a range of additional materials and building parts are considered replaced, following the service life table. For instance insulation materials and façade elements. These larger scale replacements can be seen as jumps of the line graphs. This pattern is further illustrated in Figure 2 a) and b) that show the accumulated results of the case buildings at RSP 50 years and 120 years respectively. The figures show that, in both cases, the GWP profiles start out with the first 25-30 years being practically free from replacements. For the 50-year RSP (Figure 2a), the years between 30 and 50 after the construction entail a range of replacements of minor scale. The final EoL may then involve a notable emission load. This load is especially prominent for the cases with larger amounts of timber/wood due to the stored carbon being released at the final incineration of these products. For the 120-year RSP (Figure 2b), the years between 30 and 120 after the construction entail a range of replacements of larger scale, e.g. insulation materials. These notable variations between the longer and shorter service lives point to some inappropriate definitions of the service life table in use for Danish conditions, e.g. that ground deck insulation is expected to last for only 80 years even though the ground deck itself is expected to last the same number of years as the building itself, e.g. 120 years. There may be technical deterioration of some materials, such as the insulation materials. However, replacing the ground deck insulation without removing the ground deck itself is improbable. And a scenario of

replacing the ground deck to ensure a renewed technical service life by replacing the subjacent insulating function is also highly uncertain.

Figure 1. The GWP results of the 11 case buildings for the Production and EoL stages (1a) and for the replacement stage (1b) at different reference study periods.

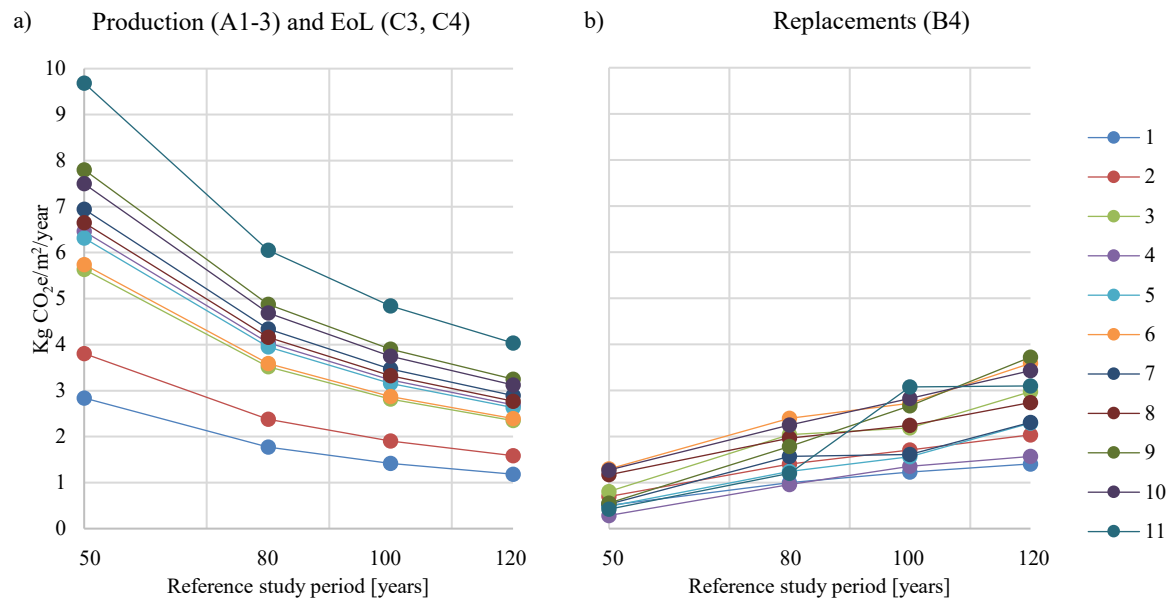
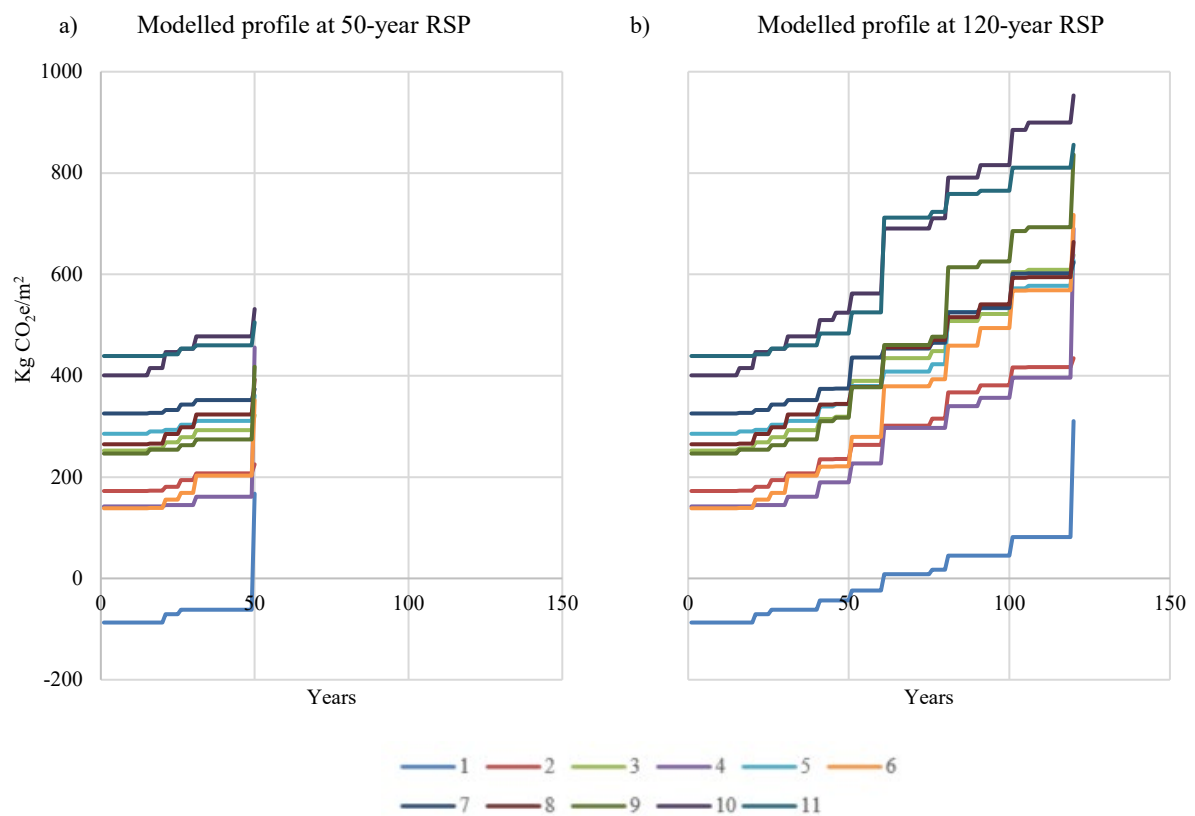


Figure 2. The accumulated impacts from the case models at an RSP of 50 years (2a) and at an RSP of 120 years (2b).



3.1. Ranking of the buildings

Figure 3 combines the impacts from production, replacement and EoL from each of the cases in the sample. From this figure, a general tendency of reduced impacts (per m² per year) can be observed between the 50-, the 80-, and the 100-year RSP, although, for the 120-year perspective, there is a slight increase in reported impact compared with the 100-year perspective.

Figure 3 further shows that the ranking of the different buildings does not change particularly by varying the RSP between 50-, 80-, and 100 years. However, at RSP of 120 years, the ranking in-between the cases changes due to several of the more durable building materials being replaced, as explained previously.

Figure 3. The GWP results of the 11 case buildings for the Production, Replacement and EoL stages at different reference study periods.

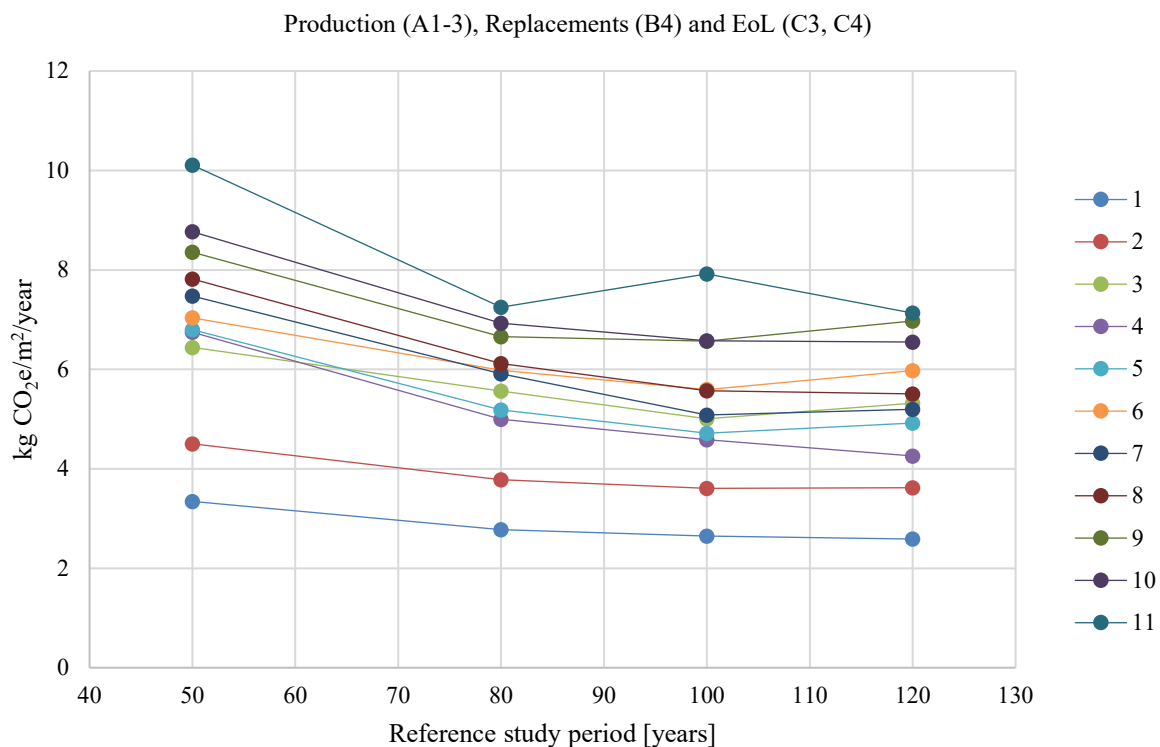


Table 2. GWP results and ranking of the 11 case buildings at 50-year RSP and at 120-year RSP

Case#	kg CO ₂ e/m ² /year at 50-year RSP	Ranking, 50 years	kg CO ₂ e/m ² /year at 120-year RSP	Ranking, 120 years
1	3.34	1	2.59	1
2	4.50	2	3.62	2
3	6.44	3	5.32	5
4	9.11	9	5.75	7
5	7.22	5	5.23	4
6	7.04	4	5.98	8
7	7.47	6	5.20	3
8	7.86	7	5.53	6
9	8.36	8	6.97	9
10	10.63	11	7.94	11
11	10.11	10	7.13	10

Table 2 explores the details of the results of the 11 cases and the ranking of the cases in relation to each other at RSPs of 50 years and of 120 years. As shown, the two best performing cases and the two worst performing cases are identical between the two RSPs. The remainder of the cases vary to some extent. However, the ranges of results from these in-between cases is also limited, e.g. varying between 5.20-5.98 kg CO₂e/m²/year for cases# 2-7 at RSP of 120 years. Hence, changes in their internal ranking is induced by small numerical differences.

The difference between the worst performing case and the best performing case is 69% and 67% for the 50- and 120-year RSP respectively. Hence, regardless of the non-linear impacts induced by replacements in a longer reference study period, there is an approximate 3-fold difference between the best and the worst cases.

3.2. Heavy versus light construction

Heavy and light facades in the cases influence results in different ways. Light facades typically have expected service lives around 50-60 years and are therefore replaced at 80- and at 100 years in a 120-year RSP. The impacts associated with light facades vary notably. An aluminium-based façade cladding in case #11 thus add significant impacts to the profile, compared with the wooden cladding in case #1. For the heavy façade structures, a different dynamic is apparent in the cases. The service life table specify the expected service life of a tile façade as being replaced once, if using a 120-year perspective. This causes the notable jumps in the line graphs in Figure 3b at year 80 for the cases #3, 5, 8 and 9. Like previously discussed in relation to the ground deck insulation, this replacement of the entire heavy façade is indeed uncertain.

3.3. Photovoltaics

Photovoltaics (PVs) have a remarkable influence on the performance of the building because the production impacts are high and the service life is relatively low (30 years), meaning that replacements are modelled one time in an RSP of 50 years, two times at RSPs of 80 and 100 years, and three times at an RSP of 120 years. In the cases with large PV installations, relative to the GFA, (#2, 6 and 8), the PV installations are major contributors to the total embodied impacts. Further, for all cases with PVs, these installations are major contributors to the particular life cycle of replacements.

3.4. Installations

Ventilations ducts and heating distribution systems are documented in five cases (see Table 1). For these, impacts are especially noteworthy in the school and in the hospital. Ventilation ducts have a large influence already in the production stage, but also in the replacement stage, where aggregates and radiators further add to high impacts, regardless of the RSP in question. For the residential buildings, (cases #5 and 9), the floor heating system is particularly emission intense. Further, impacts from the hot water storage tank are prominent due to the defined service life of 30 years.

4. Discussion

4.1. The sample

The cases in the current investigation was deliberately chosen to reflect different building types, sizes and characteristics in terms of material use and structural principles. This allows for an in-depth analysis of specific characteristics of the buildings, e.g. the effect on results for buildings with large areas of installed PVs. However, the random selection further bears the risk of having missed some parameters of relevance to the results. Further investigations on a larger sample size could improve this potential lack of attention towards other parameters.

4.2. The longer reference study periods (80-120 years)

A longer reference study period, reflecting the technical service life of the building (80-120 years, depending on type), was investigated in this study. As shown in Figure 2b, the 120-year RSP involved some dubious replacements around year 80, resulting, in general, in contra intuitive higher levels of impacts (per m² per year) for the 120-year period than for the 100-year period (see also Figure 3). This

points to the national service life table as being flawed to some extent as described earlier. However, even an updated version of a national service life table will not amend the aspect of temporal uncertainty relating to the longer RSPs. 120 years is an improbable amount of years on which to use year 2020-data for material production and scenarios (e.g. EoL scenarios). In general, impacts induced by replacements double in Figure 1b from using a 50-year perspective to using a 80-year perspective, and the 120-year perspective adds approximately another 50% from the 80-year perspective. This deterministic modelling of production and replacements can be considered highly uncertain, and points to the relevance of choosing a shorter reference study period.

An additional drawback about the longer time perspective concerns the ethics of effectively allocating impacts to future generations inhabiting the building [10]. If the building is assessed with a 100-year RSP and found to cause embodied impacts of e.g. 5.7 kg CO₂e/m²/year (case #8), the persons purchasing the house in year 60 after construction, will, so to say, inherit an environmental load. Regardless of the fact that approximately half of the total emissions, in fact, occurred at the initial production and construction of the building (see Figure 2).

A final perspective on using the required service life of the building (80-120 years) as RSP, revolves around the difficulties of plausibly estimating the actual service life of buildings. Østergaard et al. investigated the actual service life of Danish buildings by statistically analyzing 21,000 buildings demolished between 2009-2015, concluding an average service life of these buildings of 70 years with buildings in the capital region showing notably shorter service lives with a mean of 60 years [11]. O'Connor investigated building demolitions in Minneapolis/St. Paul. She found that most demolitions of residential buildings were found in the category of 76-100 years old whereas almost half of the demolished non-residential buildings were in the age category 26-50. She further illuminated how only 38 % of the buildings were demolished due to their physical condition. The remaining demolitions were due to, for instance, area redevelopment or the building being unsuitable for meeting the needs of owner/tenants [12]. Hence, the actual service life of buildings vary widely, and is not convincingly correlated with the physical conditions.

4.3. The shorter reference study period (50 years)

Although used widely in research and practice, the 50-year RSP is an arbitrary choice that does not reflect any specific event in the life cycle of the building, and it is likely that the building in fact will stand for many more years to come. However, a shorter RSP of 50 years partly avoids the shortcomings of the longer RSPs as detailed above. Further, an RSP of 50 years moves focus towards the initial life cycle stages and the design choices made, which is better in line with the urgency of current greenhouse gas reductions.

Buildings constructed with large amounts of materials with expected service lives parallel to the building itself, for instance brick tiles, may find the annualized results of a 50-year RSP disappointingly high if zooming in on the specific material. This is because the impacts from construction are distributed over less amount of years. However, from a polluter-pays perspective this is only fair, because the actual emissions associated with the production of these materials happen around the time the building is constructed. Hence, the decision to integrate a durable, but potentially highly emissive material, cannot be reversed at a later stage in the life cycle of the building. However, on a whole-building level, the rankings of the current study do not change notably between the buildings employing different types of material strategies in terms of durable materials vs shorter-lived and less emissive materials.

5. Conclusions

This study aimed to investigate different RSPs in the development context of a Danish LCA method for buildings. Based on a sample of 11 case buildings, the changes in ranking and the pros and cons of shorter vs longer RSP was analyzed. Results showed that the ranking between the buildings did not change for the two worst performing and the two best performing. The ranking of the cases in-between the extremes altered to a minor extent, considering the narrow range of results for these average building cases. Hence, on a whole-building level, the ranking between better and worse performing buildings does not change notably between the RSP investigated in this study.

The pros associated with a longer RSP primarily concern the basic approach of modelling a full life cycle of a building as prescribed by, for instance, the EN 15978 standard. However, the longer RSPs have serious drawbacks regarding the increasing uncertainties associated with the scenarios. Further, annualizing results of longer RSPs entail a fundamental ethical issue of effectively allocating environmental loads to future generations. These specific drawbacks of uncertainty and distribution are reduced by using an RSP of 50 years. By use of a 50-year temporal scope, it is still possible to include the impacts from shorter-lived building materials and components, which are expected to arise in the years 30-50 after construction. However, with a shorter temporal perspective, more emphasis should be put on the material related emissions that take place here and now; current emissions that urgently need reductions in light of the shrinking, global carbon budgets. Further development of target values for building LCAs should integrate this important perspective.

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